EXPLODING METALLIC FOILS FOR SLAPPER, FUSE, AND HOT PLASMA APPLICATIONS: COMPUTATIONAL PREDICTIONS, EXPERIMENTAL OBSERVATIONS

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ABSTRACT

A new computer model for determining the time-dependent behavior of exploding metallic foils is discussed. The model emphasizes the hydrodynamic expansion of exploding foils and gives insight into the temporal evolution of the material density and temperature as well as the nonlinear electrical circuit interaction. The model reproduces experimental observations very satisfactorily. Predictions of the model are also discussed. An experimental facility to verify or modify the predictions and to generate an atomic data base is described.

INTRODUCTION

The Los Alamos TRAILMASTER foil implosion program [1] is intended to produce a source of intense radiation for material and fusion studies. Unique to the Los Alamos program is using as the prime power source magnetic flux compression generators driven by high explosives. As has been discussed in a number of papers at this conference, TRAILMASTER provides the impetus for extensive development of flux compression generators, fast-opening switches, power flow techniques, and experimental diagnostics. Concurrent with the experimental program is an effort to develop computer codes capable of modeling all aspects of the implosion system.

A key technological impediment to the ultimate success of the TRAILMASTER program at multimegajoule energy levels is the unavailability of a suitable fast-opening switch. In a system using existing generator technology, an opening switch, or combination of switches, might be required to carry over 50 MA of current for over 200 μs and then interrupt the current through it in significantly less than 1 μs. One candidate for the switch is an exploding metallic foil, or "fuse."

To begin evaluating the utility of fuses at high energy levels, we recently formulated a zero-dimensional computer model of the physical and electrical behavior of a metallic foil/insulator sandwich [2]. In contrast to many other approaches to modeling the electrical behavior of exploding metallic foils and wires, our model is more or less a "first-principles" approach and does not build directly upon experimental data. The model emphasizes the post-"burst" hydrodynamic expansion process and hence gives insight into the temporal behavior of the foil temperature, density, and pressure as well as its electrical interaction. Incorporated into the model is an assumption of homogeniety based on sophisticated one-dimensional magnetohydrodynamic computer code computations of exploding foil behavior. Energy loss by radiation and thermal conduction are assumed to be negligible, assumptions also supported by one-dimensional computations.

The simplifying assumption of homogeniety makes possible a computer code requiring little computer operating time to compute the behavior of a single foil. Hence, the model makes possible extensive exploration of parameter space. As in more sophisticated, and more expensive, one-dimensional simulations, our model requires the use of an atomic data base which gives material pressure, internal energy, and electrical conductivity as functions of density and temperature. During a typical exploding foil experiment, the foil density may decrease by over three orders of magnitude and the temperature of the foil may increase by over two orders of magnitude. Such a density and temperature range transcends the solid, liquid, and vapor phases and as such taxes the most powerful theoretical tools for determining the atomic data base. The validity of any predictions based on our exploding foil computer model depends upon the validity of both the atomic data base and our simplifying assumptions.

The computed predictions we reported in [2] demonstrate the importance of the foil material's hydrodynamic behavior on its electrical performance. According to the predictions, the hydrodynamic behavior, hence the electrical performance, of an exploding metallic foil depends upon the actual dimensions of the foil, not merely its cross-sectional area, and upon the mass of the confining insulator. Because different foils can take different trajectories through density-temperature parameter space, the computations predict that the resistance increase of a foil does not depend solely upon the energy deposited within the foil or solely upon the action integral of the current through the foil. The computations predict that, at least in certain regimes, the dominant effect of the confining insulator is merely inertial. Most important, the model computations predict that fuses offer the possibility of achieving multimegajoule, submicrosecond metallic foil implosions using as the prime power source long time scale magnetic flux compression generators driven by high explosives.

This paper reports on an effort we have initiated since completing [2] to assess the validity of the predictions based upon our foil model and the validity of the atomic data base upon which the predictions depend. Although our ultimate interest is in using exploding metallic foils as switching elements in multimegajoule systems, we have realized that our computer modeling techniques apply to exploding metallic foils used for other applications such as the initiation of high explosives and the acceleration of flyer plates for equation-of-state and shock damage studies [3]. In contrast to actual fuse applications, where the method of construction leads to some ambiguities, these low-energy applications appear *a priori* to satisfy the assumptions of our foil model, so deviations between computed behavior and experimentally observed behavior appear to indicate errors in the atomic data base.

ATOMIC DATA BASE

Although equations-of-state (pressure and internal energy as a function of density and temperature) transcending the parameter range of

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14. ABSTRACT
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interest have been available for many years, realistic theoretical calculations of the electrical conductivity are just beginning to emerge. Much of our recent effort has been the evaluation of several currently available models of electrical conductivity. At present, we have concluded that a normalized model of electrical conductivity based on the work of More and Lee [4,5] is the most reliable.

Our complete exploding foil model enables computation of the actual time dependency of the physical parameters of interest for an exploding foil system. However, even before performing a time-dependent computation, we can gain insight into the behavior of exploding foils by examining the atomic data base. For a homogeneous material with a constant length in the direction of current flow, the material's resistance increase is

$$R/R_0=\eta\rho/(\eta_0\rho_0), \qquad (1)$$

where R is the resistance, η is the electrical resistivity, ρ is the mass density, and a subscript 0 indicates an initial quantity. In accordance with Eq. (1), not only does the resistance increase depend linearly on the resistivity, as is generally acknowledged, but it also depends on the material density. Because the resistivity will in general vary nonlinearly with the density, which decreases rapidly as an exploding foil expands, Eq. (1) implies a strong dependence of the electrical performance on the hydrodynamic behavior.

It is traditional in exploding foil and wire work to consider the resistance increase to be only a function of the energy deposited or, equivalently, to be only a function of the current action integral. However, in [2] we showed that the More/Lee electrical resistivity coupled with a full-range equation-of-state predicts that the increase and subsequent decrease in resistance as energy is deposited depends strongly upon the material pressure. Thus, we emphasized the hydrodynamic behavior of the exploding metallic foil. Because the electrical resistivity is a function of both density and temperature, the resistance increase R/R_0 as given in Eq. (1) is also a function of density and temperature. Figs. 1 and 2 show the More/Lee predicted resistance increases for aluminum and copper, respectively. At low temperatures and somewhat expanded densities, Fig. 1 predicts that very large resistance increases are possible. Although quantitatively different, other available resistivity models predict a similar region of large resistance increase. We note that actual experimental determination of the electrical resistivity for aluminum and copper has been performed for temperatures up to only about 0.5 eV and densities no smaller than about 1/3 of normal density. Hence there is as yet no actual verification of large resistance increases in some ranges of density-temperature parameter space.

In [2], by exploring a wide range of parameter space with our exploding foil model, we were able to find, for a particular generator/electrical circuit configuration, a fuse that would couple nearly 50% of the theoretically maximum possible energy to an imploding foil load. That particular fuse carried an electrical current which reached over 70 MA in 270 μs, then transferred over 40 MA to the imploding foil load which reached a kinetic energy of 6 MJ in less than 1 μs. The trajectory through density-temperature space for that fuse is shown in Fig. 3. The fuse reached a peak resistance increase of 10^4, as seen in a comparison of Fig. 3 with Fig. 1. Hence, for ultimate TRAILMASTER applications, the major issues are whether the regions of high

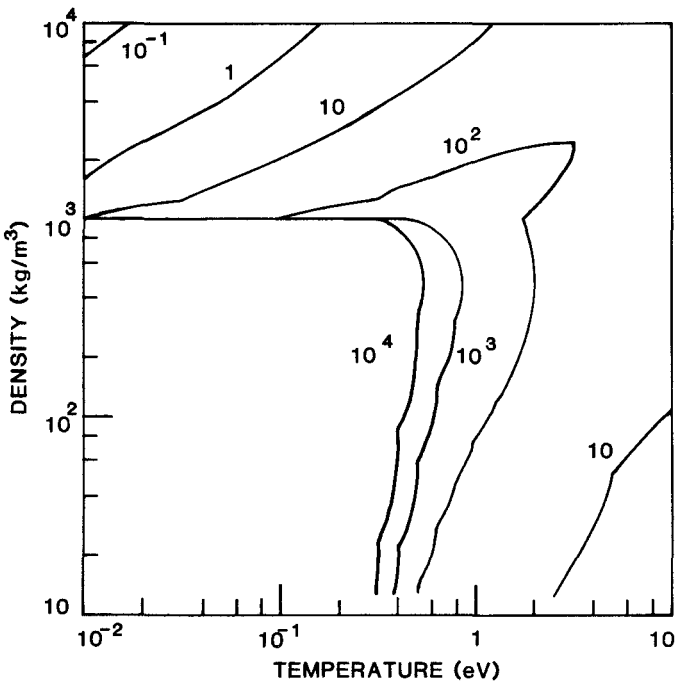

Fig. 1. Contours of aluminum resistance increase R/R_0 in the temperature-density plane (T_0=0.025 eV, ρ_0=2.7 x 10^3 kg/m^3).

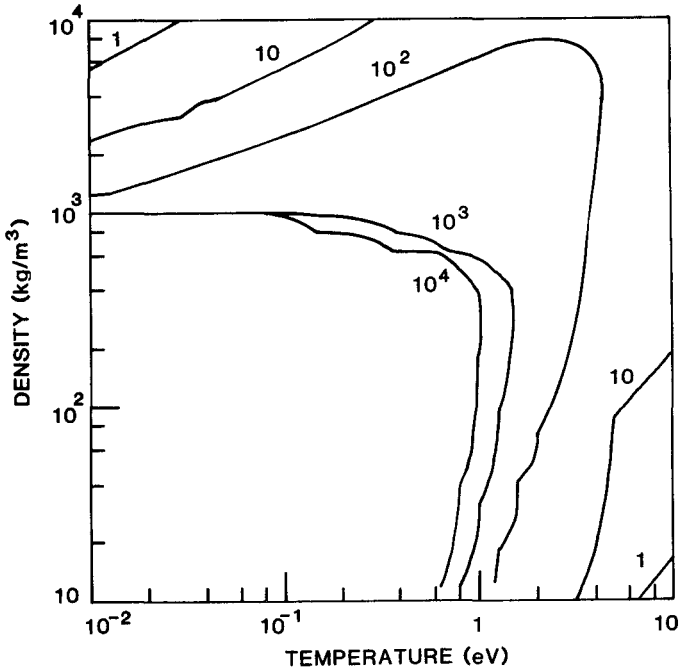

Fig. 2. Contours of copper resistance increase R/R_0 in the temperature-density plane (T_0=0.025 eV, ρ_0=8.93 x 10^3 kg/m^3).

resistance increase in density-temperature space actually exist, and, if they do exist, whether the hydrodynamics of an exploding foil can be controlled so the regions of high resistance may be accessed.

COMPUTATION VS. EXPERIMENT

Our most recent effort has been to examine existing data on exploding foils to determine how well we can computationally reproduce experimental observations. In essence, we

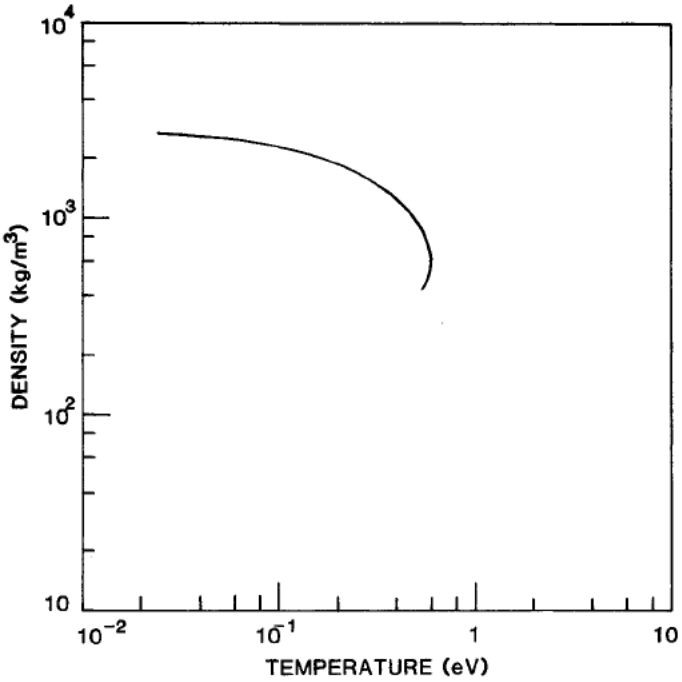

Fig. 3. Density-temperature trajectory for the tandem generator aluminum fuse discussed in [2]; time is a parameter along the trajectory and increases clockwise along the trajectory.

attempt to perform on the computer the same experiment as performed in the laboratory; each relevant experimental parameter is an input number for our simulations. Our computations show that all relevant parameters such as capacitance, inductance, and foil dimensions must be precisely characterized if conclusions about the validity of the atomic data base are to be drawn.

Figure 4 shows a comparison between experimental data obtained on the Lawrence Livermore National Laboratory electric gun [3] and our corresponding computations. In Fig. 4, the experimental curve has been normalized to approximately match the computed pre-burst dI/dt, since currently there is some uncertainty in the actual experimental calibration. Experimentally, the two different foils show significantly different electrical behavior, and the computations match the experimental waveforms very satisfactorily. The density-temperature trajectories of the two foils according to our exploding foil model are shown in Fig. 5. Because of the amount of stored energy available, both foils are heated rapidly beyond the vaporization phase and the trajectories miss the regions of high resistance. In [2] we showed that the resistance increase as a function of deposited energy can vary significantly because of hydrodynamic behavior. Equivalently, the resistance increase as a function of the specific current action ($\int I^2 dt/A_0^2$) can also vary significantly, as is illustrated in Fig. 6 for the two foils of Fig. 4. The action at peak resistance in Fig. 6 agrees well with that determined experimentally for exploding wires [6], but the post-burst behavior is significantly different. The agreement between the experiments and the computations shown in Fig. 4 appears to verify the atomic data base along the trajectories of Fig. 5, but unfortunately the experiments give no insight into the existence of a region of extremely large resistance increase.

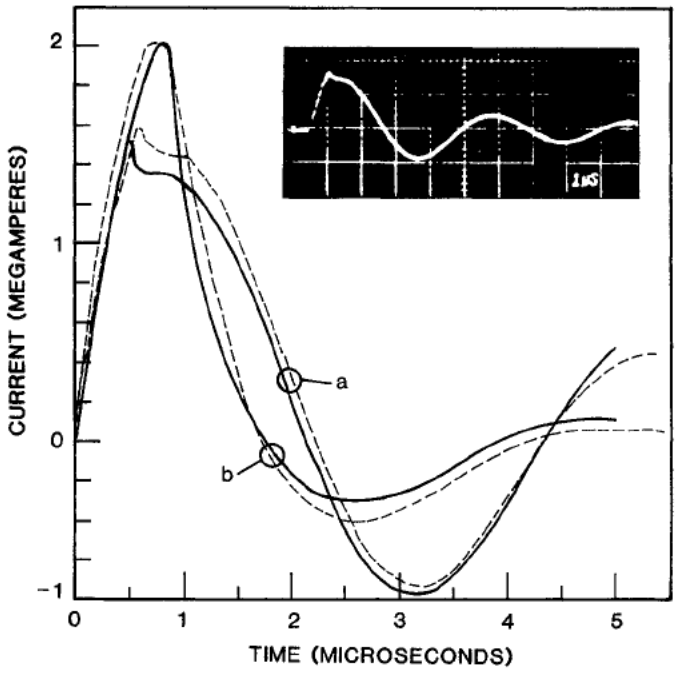

Fig. 4. Computed (solid) and experimental (dashed) electrical current for the LLNL electric gun aluminum foils(V=90 kV, C=15.1 μF, L=25 nH, R=1 mΩ, δ=50.8 μm, $\ell=w$, tamper $\rho\delta$=0.427 kg/m²): (a) w=5.08 cm; (b) w=10.2 cm. The inset shows the actual oscilloscope trace for (a).

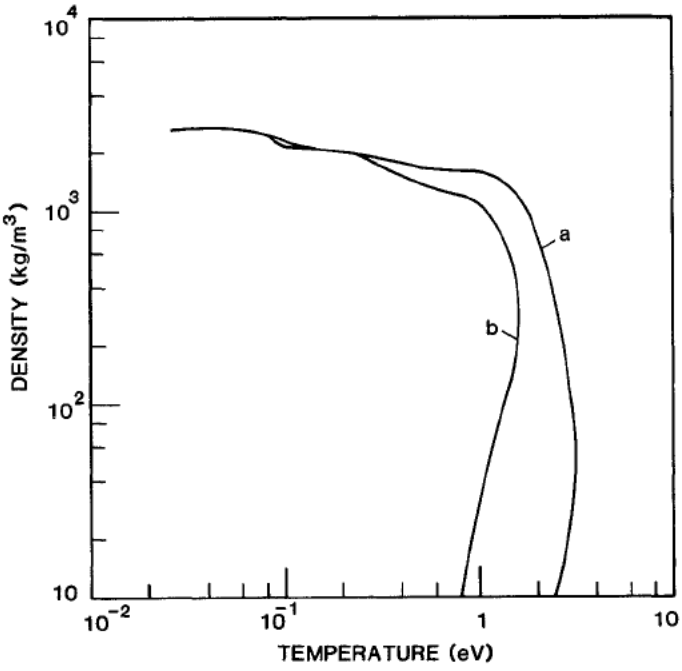

Fig. 5. Density-temperature trajectories for the foils of Fig. 4.

At Los Alamos we have used exploding copper foils to drive small projectiles, or "slappers," to detonate high explosives. Figures 7–9 show comparisons between experiment and computation for two identical foils in circuits having differing inductances. If the foils did not undergo a large resistance increase, the current of Fig. 7a would rise to a peak of 29 kA at 0.45 μs and the waveform would be sinusoidal. The waveform of Fig. 7b would also be correspondingly different. The small "bridge"

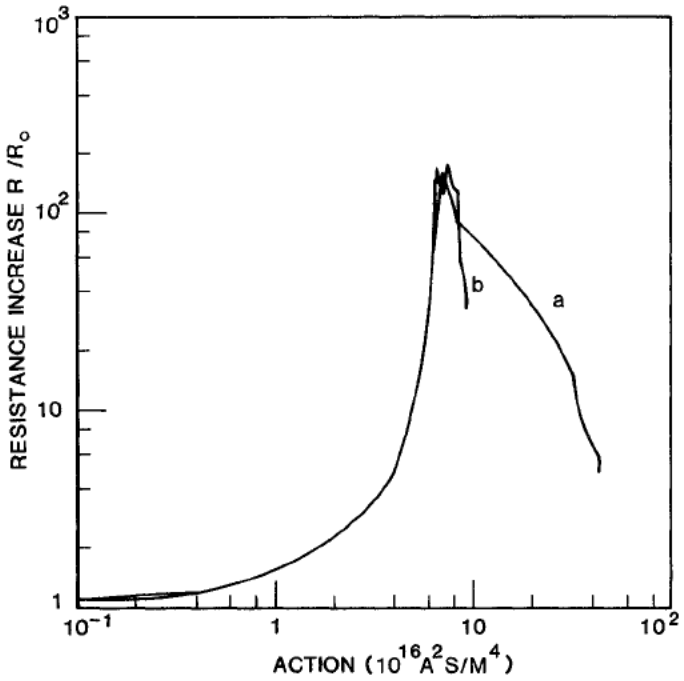

Fig. 6. Resistance increase R/R_0 as a function of specific action for the foils of Fig. 4.

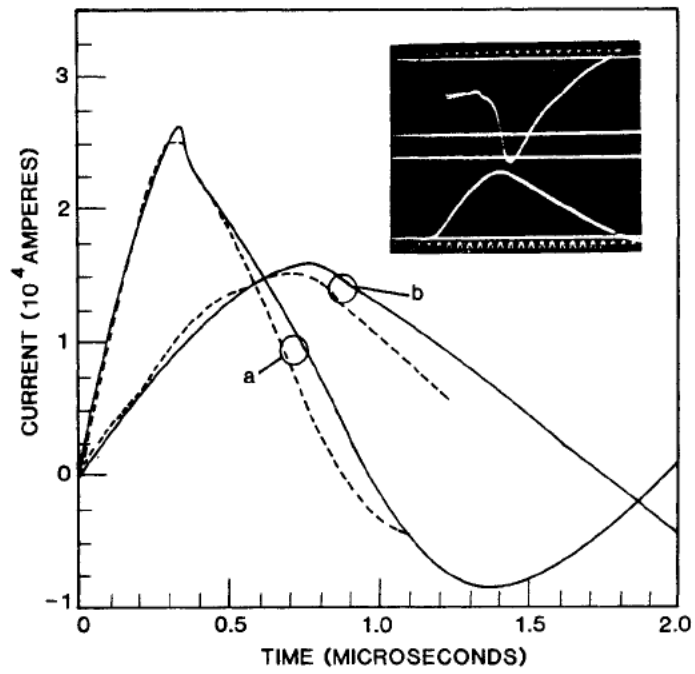

Fig. 7. Computed (solid) and experimental (dashed) electrical current for the Los Alamos slapper test facility copper foils(V=5 kV, C=2 μF, R=30 $\mu\Omega$, δ=20 μm, ℓ=1 mm, w=1.12 mm, tamper $\rho\delta$=0.291 kg/m^2): (a) L=45 nH; (b) L=160 nH. The inset shows the actual voltage and current oscilloscope traces for (a).

foils are constructed by cutting out sections of an otherwise uniform copper ribbon which is three times wider than the bridge. The actual cross-sectional area was not determined precisely, and there is some ambiguity in the appropriate length, so to achieve the agreement shown in Figs. 7-9 we have varied dimensions of the foil by as much as 12% from nominal. In addition, to match the flyer velocity of Fig. 9 we have used a flyer mass of nearly 265% of nominal; since the electrical waveforms are not significantly affected by a variation in flyer mass, we suspect there may be errors in the pressure portion of the equation-of-state.

The density-temperature trajectories corresponding to Figs. 7-9 are shown in Fig. 10. As for the aluminum electric gun foils of Fig. 5, a peak temperature of a few electron volts is reached before further expansion and cooling.

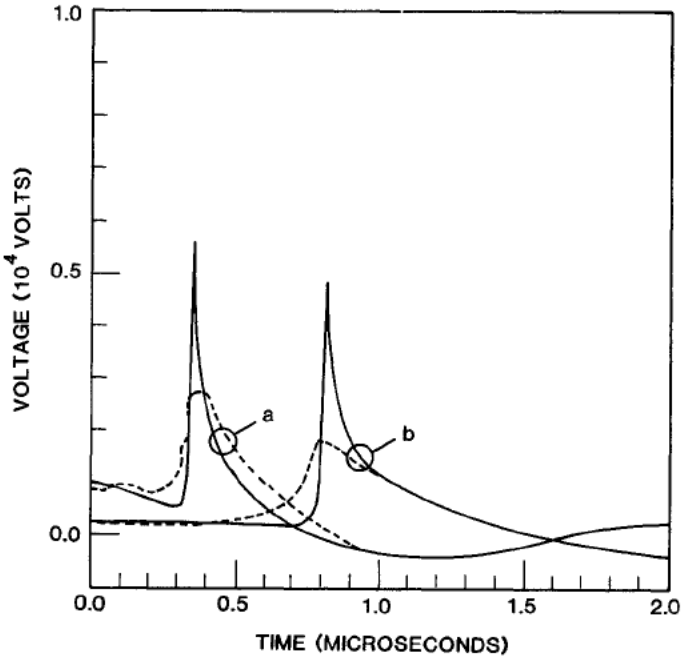

Fig. 8. Computed (solid) and experimental (dashed) voltages for the foils of Fig. 7.

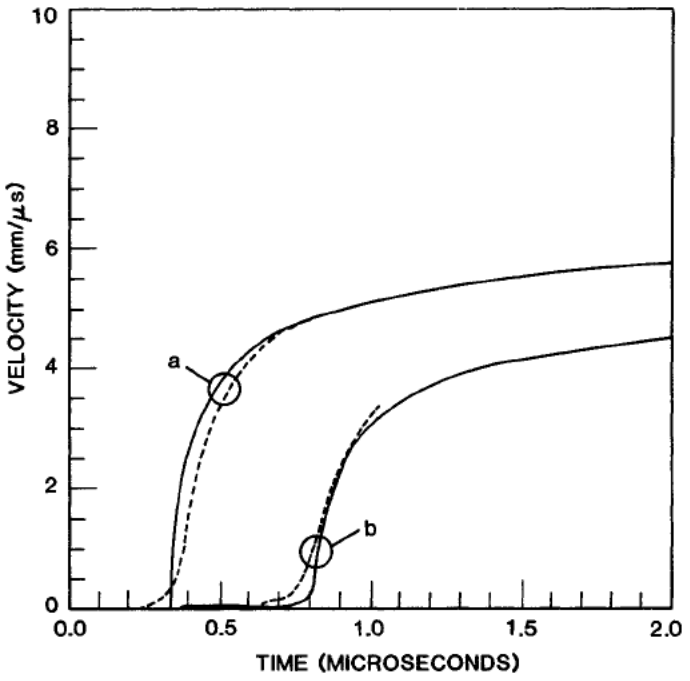

Fig. 9. Computed (solid) and experimental (dashed) expansion velocity for the foils of Fig. 7.

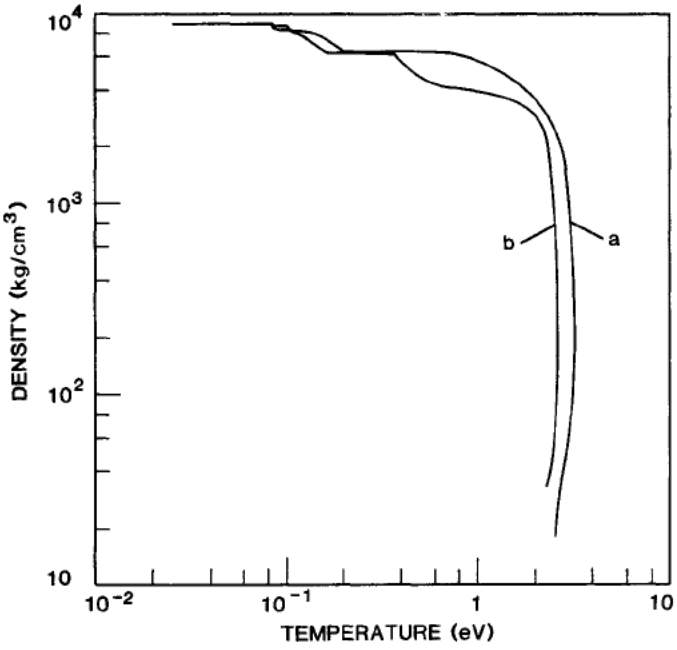

Fig. 10. Density-temperature trajectories for the foils of Fig. 7.

The trajectories of Figs. 5 and 10 typify exploding foils used to generate high pressures to accelerate a flyer plate.

PROPOSED EXPERIMENTS

A comparison of Fig. 10 with Fig. 2 shows that the slapper experiments for which we have data do not probe the region of high increase in resistance. Our exploding foil model predicts that the high-resistance region can be accessed merely by increasing the length of the exploding foil. Figs. 11 and 12 show model predictions of current waveforms and the corresponding density-temperature trajectories for the longer exploding foils. As the foil length is increased, the current is interrupted rapidly, that is, the slapper becomes a fuse.

We are readying a laboratory facility to perform systematic parameter variations to verify or modify our model predictions of the behavior dependency on the varied parameters. As illustrated in Fig. 12, we should be able to map out an extensive area in density-temperature space and determine whether regions of high increase in resistance do exist and determine how large a resistance increase is possible through proper control of the hydrodynamic behavior of the exploding metallic foil.

Our upgraded laboratory facility will employ a completely microprocessor-controlled system for firing and acquiring data on exploding metallic foils. Voltage signals will be obtained by a passive differential probe connected near the exploding foil. Current signals will be obtained by a current viewing resistor in series with the discharge capacitor and exploding foil. The rate of expansion of the exploding foil will be measured by a modified VISAR(Velocity Interferometer System for Any Reflector) in which velocity information is recorded continuously during an experiment [7,8]. The four raw signals (two electrical, two VISAR) will be acquired from Tektronix 7912AD digitizers with time resolutions of a few nanoseconds or better. All signals will be time calibrated to correct for digitizer time-base inaccuracy and nonlinearity. The current and voltage signals will be amplitude calibrated. During experiments, time reference fiducials will be recorded just before and after the dynamic signals to provide precise time correlation between signals and as a redundant check on time calibrations. Care will be taken in setting up the equipment to ensure identical time relations between all signals and their time fiducials. The calibrated signals, including their time fiducials, will be stored on floppy disks for subsequent reduction by the DEC LSI 11-23 microprocessor that communicates with and controls the digitizers.

Because of the smallness of each experimental shot and because the firing and data acquisition sequence is microprocessor controlled, we will be able to acquire data in

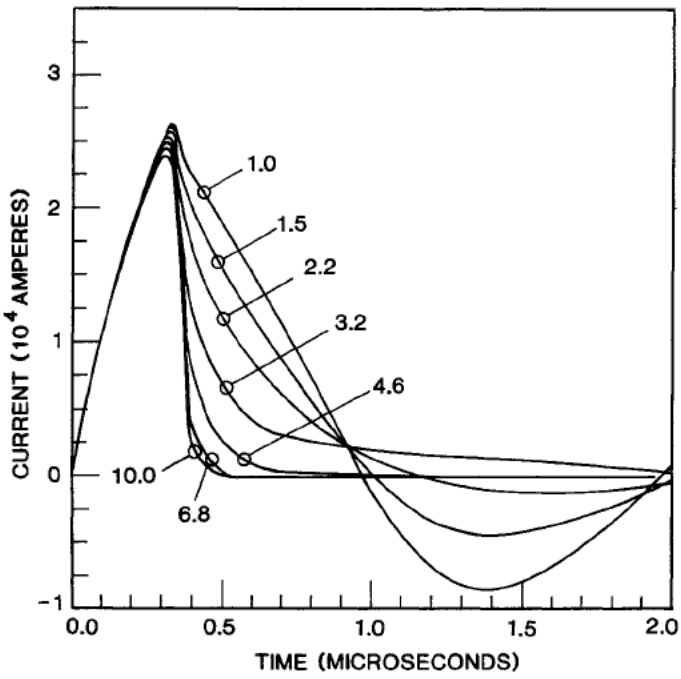

Fig. 11. Predicted electrical current for the parameters of Fig. 7a and foil length (mm) as indicated.

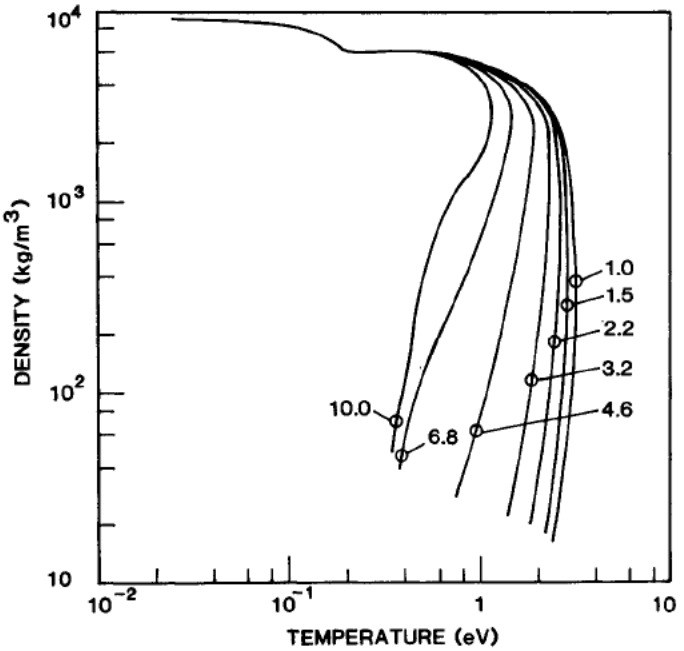

Fig. 12. Density-temperature trajectories for the foils of Fig. 11.

approximately 2 min. per shot. The subsequent data reduction will take a similar length of time. Hence, it should be possible to perform an extensive series of parameter variations in a very short time. The data storage on floppy disks provides a means for directly communicating with the computers at our Central Computing Facility, where our computational modeling takes place. We therefore can anticipate a nearly completely automated, extensive, detailed comparison between experimental observations and computational predictions.

ATOMIC DATA BASE GENERATION

Considering the difficulty of doing theoretical calculations of the material properties for the atomic data base used in our exploding foil modeling, it would be quite surprising if our systematic variation of parameters would merely confirm the validity of our modeling and the atomic data base.

We believe that our experimental apparatus makes it possible to actually generate the atomic data base. Our experimental facility will provide voltage and current waveforms and flyer plate velocity. The latter can be integrated to determine the flyer position. If we postulate that our one-dimensional magnetohydrodynamic computations are qualitatively correct, we conclude that the foil material is homogeneous and that the flyer plate position is an indication of the instantaneous foil density. From the electrical signals we can determine the instantaneous resistance of the foil and the amount of energy delivered to the foil. The foil density and the resistance give the resistivity in accordance with Eq. (1). A homogeneous material has a linear velocity profile (as used in our exploding foil model [2]) so the flyer velocity allows determination of the foil kinetic energy. The delivered electrical energy, corrected for inductive energies and the kinetic energy, gives the material specific internal energy. The flyer plate acceleration gives the material pressure. Hence, both the electrical resistivity and material pressure can be determined as a function of density and specific energy along the trajectory in density-specific energy space. By a proper variation of parameters, the entire relevant density-specific energy space can be mapped out. Normally, resistivity and pressure are determined as functions of density and temperature, but in our "energy-based" modeling temperature is merely an index and is not explicitly required.

CONCLUDING REMARKS

As part of the Los Alamos TRAILMASTER imploding foil program, we have begun to evaluate the usefulness of exploding metallic foils--fuses--for switching elements in pulsed power inductive store systems. Our approach has been a first-principles computational one, and we are now attempting to determine the validity of our computational methodology and the atomic data base on which it depends.

Qualitatively speaking, although we have certainly not performed an extensive literature search, we believe that our computed results agree with most experimental observations of exploding metallic foils in a variety of different contexts. As we have shown in this paper, we have obtained excellent quantitative agreement between our computations and some reasonably well-characterized experiments.

The goal of any computational effort such as ours is to provide guidance for an experimental effort. Our computations have provided an incentive for performing an extensive, detailed characterization of exploding metallic foils over a wide range of parameters. We can expect continual "bootstrapping" between our experimental program and our computational program.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge conversations with many people throughout the country who have been involved with exploding metallic foils. It is premature to predict the integrated outcome of our present investigations, but we know that each individual to whom we have talked has helped us reach our present level of understanding. Dr. Richard More and Dr. Yim Lee of the Lawrence Livermore National Laboratory have provided the results of their theoretical resistivity calculations. Dr. Robert Reinovsky, Maj. William McCullough, and Capt. Jerry Bueck of the Air Force Weapons Laboratory have provided experimental data and unique insight which have stimulated this work. Drs. James Goforth, Dennis Erickson, and Gerald Parker of Los Alamos, Richard Weingart, William vonHolle, Henry Chau, David Abe, and Ken Froeschner of the Lawrence Livermore National Laboratory and Gerald Houston, Andrew DeMana and Dale Schaeffer of the Mound Laboratories have provided experimental data on exploding metallic foils, and Prof. Ronald Lee of Kansas State University has provided the important link between Livermore, Mound, and Los Alamos. Dr. William Lupton of the Naval Research Laboratory has discussed with us experimental observations of exploding wires which we believe could be reproduced by a wire version of our exploding foil computer code.

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